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USE OF HARDWARE-IN-THE-LOOP SIMULATION (HWIL) IN THE DEVELOPMENT, TEST, AND EVALUATION OF MULTI-SPECTRAL MISSILE SYSTEMS

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ABSTRACT

The U.S. Army Aviation and Missile Command (AMCOM) Advanced Simulation Center (ASC) provides hardware-in-the-loop (HWIL) simulation support to Program Executive Officers (PEO) and Project Managers (PM) who are responsible for developing and fielding precision guided missiles and sub-munitions for the U.S. Army. The ASC is also engaged in cooperative HWIL simulation tasks supporting other Armed Service Agencies, NATO and other U.S. allies. HWIL simulation provides a means of exercising missile guidance and control hardware in simulated flight, wherein the missile sensors are stimulated with input signals which make the system behave as though it were in actual operation. Real-time computers are used to control the target and countermeasure signatures and battlefield scenarios. Missile flight dynamics, responding to the commands issued by the guidance and control system hardware/software, are simulated in real-time to determine the missile trajectory and to calculate target intercept conditions. The ASC consists of 12 HWIL simulation facilities developed over a period of 20 years. These facilities contain special purpose infrared and RF signal generation equipment, flight motion simulators, radiation chambers, optics, and computers. They provide in-band target signatures, countermeasures, and background scenarios in the microwave, millimeter wave, infrared and visible regions of the electromagnetic spectrum. The ASC HWIL simulation facilities are an important source of test and evaluation data and have a critical role in all phases of a missile system life cycle. The development of a new generation of missile systems that use multi-spectral seekers has imposed unique and difficult requirements on ASC HWIL simulation facilities. For the past three years, the U.S. Army Aviation and Missile Command (AMCOM) has been developing a HWIL simulation facility to test common aperture multi-spectral missile seekers. This paper discusses the problems encountered during the development of this facility, the solutions, and the resulting capability of this unique HWIL simulation facility.

The ASC is managed and operated by the Systems Simulation and

Development Directorate of the Missile Research, Development, and Engineering Center, Redstone Arsenal, Alabama.

INTRODUCTION

Over the past 30 years, the U. S. Army Aviation and Missile Command's (AMCOM) Advanced Simulation Center (ASC) has utilized Hardware-in-the-Loop (HWIL) simulations as an important tool to support the development of advanced Radio Frequency (RF), Millimeter Wave (MMW), Infrared (IR), and Electro-Optical (EO) guided weapon systems. Recently, the ASC began development of a simulation facility to support HWIL simulations of a new generation of missile systems which utilize dual-mode MMW and IR common-aperture seekers. By using separate sensors in a complementary manner, these systems will have many advantages over traditional single-mode (MMW or IR) guided systems operated independently. The MMW sensor has superior target acquisition at long range, meets search requirements through its larger beamwidth, and is not disabled by diverse weather conditions. The IR sensor has excellent terminal accuracy while maintaining a small form factor. Unfortunately, when compared to their single-mode counterparts, the implementation of simulation facilities to support the design, development, and testing of these advanced concepts is significantly more difficult. The foundation of HWIL simulation is the implementation of real-time closed-loop simulation functionality. The unit under test, whether a missile seeker or human decision-maker must operate in a realistic environment. The preference in HWIL simulation is to simulate as much of the natural environment as is practical. For this reason in-band projected simulation is preferred to signal injection. In-band simulation provides sensor stimulation at the natural wavelengths and through natural transmission media. For example, an IR missile seeker will be presented a projected scene within its sensor waveband through its optical system. Injection on the other hand convolves the effects of radiative transfer, optics, and translation into a digital model which then drives a scene generator whose output is injected into the sensor signal processing electronics. A lot of the test article is summarily bypassed in this approach. At the AMCOM, Missile Research and Development Center (MRDEC), Systems Simulation and Development Directorate (SS&DD), efforts are currently underway to implement an in-band HWIL simulation facility to test the new generation of dual-mode common-aperture seekers. The approach being taken is to use in-band sensor stimulation and permit natural sensor movement as much as possible via a three-axis flight table. **Figure 1** provides a three-dimensional perspective of this new HWIL simulation facility that is known as the Millimeter Wave and Imaging Infrared Simulation System (MMW/I^{2}RSS). As was previously reported in past papers, the primary components of the facility are the anechoic chamber, flight table, antenna array and MMW signal generation hardware, IR projector and optics, simulation computers, Computer Image Generator (CIG), and the dichroic beam combiner and support tower [1-3]. The Research and Development (R&D) into the majority of these components is largely complete. The status of these component parts is reported in other papers.[1-13]. The simulator performance relative to these sub-systems is reviewed in Section 2. Reported in this paper is the status of the dichroic beam combiner and support structure.

The dichroic beam combiner and its associated support structure are the primary focus of research and development efforts at

AMCOM relative to the development of a dual-mode simulation facility. At present AMCOM is utilizing a dichroic beam combiner based on a dielectric slab with IR reflective coating. As was indicated in Figure 1, it is necessary that the IR projector be positioned in a manner that minimizes the potential interference or interaction with the MMW signal. This is accomplished by rotating the dichroic beam combiner at some angle relative to the MMW line of sight. Accordingly, the beam combiner functions as a flat fold mirror for the IR. The dichroic beam combiner under development is discussed in more detail in Section 3.0. The support structure is discussed in Section 4.0.

SIMULATOR OVERVIEW

Figure 1 shows the major components of the simulator configured for full in-band testing of a dual-mode, common-aperture system. As shown in the figure, the major components of the simulator are the anechoic chamber, the MMW signal generation sub-system, the IR scene generation/projection sub-system, the flight motion simulator, the digital computer, and the dichroic beam combiner element. The performance of each identified component is critical to the implementation of a successful HWIL simulation. The ultimate success of the simulator is primarily dependent on the characteristics of three of these components: the MMW signal generation sub-system, the IR scene generation/projection sub-system, and the dichroic beam combiner element. The ASC has successfully implemented single-mode facilities which can readily support HWIL simulations of MMW or IR guided weapon systems.[1] This experience is proof that the MMW and IR related components can be successfully implemented. The current performance expectations for the MMW signal generation and IR scene generation/projection sub-systems are given in **Tables I and II.** More detail is provided on the IR projection system in a paper presented at this conference.[2]

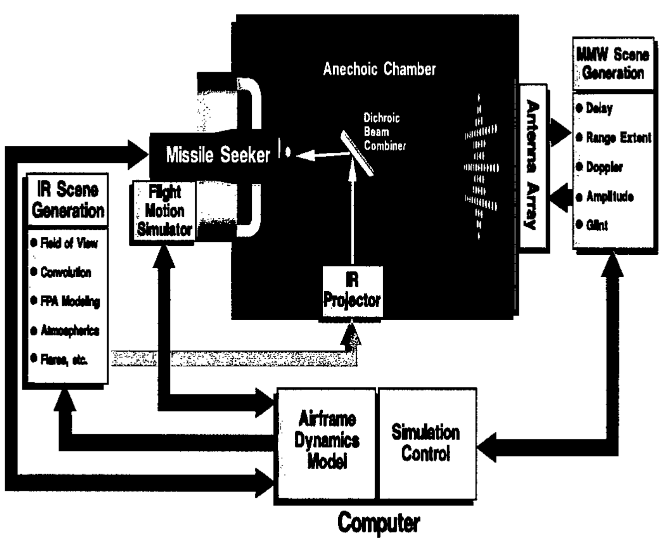

Figure 1. Dual-Mode Common-Aperture MMW/IR Simulator Overview

Performance Parameter	Value
Anechoic Chamber Size	'L x 'W x 'H
Path Length	26'
Operating Frequency	W-Band
Main Array FOV (half angle)	3.0°
Horizontal Line Array FOV (half angle)	7.0°
Polarization	Elliptical
Instantaneous Bandwidth	2000 MHz
Update Rate	1 MHz
Position Accuracy	1 mrad
Independent RF Channels	Two

Table I. Millimeter Wave Performance Characteristics

Performance Parameter	Value
Spatial Resolution	256 x 256
Number of Lasers	64
FOV	TBD
Exit Pupil Size	TBD
Effective f/#	TBD
Emission Wavelength	4.7 micron
Field Rate	16 KHz
Frame Rate	8 KHz
Maximum Output Power	$>1.16 \times 10^{-3}$
Maximum Apparent Temperature	600° C
Minimum Apparent Temperature	10° C
Dynamic Range	1000:1
Amplitude Resolution	12 bits
Stability Error	< 1 bit
Repeatability Error	< 1 bit
Laser Temporal Response	< 60 ns
Thermal Crosstalk	none

Table II. Infrared Projector Performance Characteristics

DICHROIC BEAM COMBINER

As shown in Figure 1, the dichroic beam combiner element is placed in front of the flight motion simulator with the geometrical center aligned with the boresight of the Unit Under Test (UUT). The adjustable static mount is used for precise alignment. As with previous ASC MMW simulations, Synthetic-Line-of-Sight (SLOS) is used to simulate the target to interceptor geometric relationship. In order to adequately simulate target and clutter angle glint, the beam combiner element diameter is large enough to subtend the 3 dB beamwidth of the MMW antenna array. The relatively large size of the dichroic element also minimizes phase and amplitude distortion of the simulated radar return. The performance characteristics of the beam combiner element are shown in Table III.

Parameter	Value
Size (diameter)	24"
RF Insertion Loss (dB)	≤ 2
IR Reflection	≥ 0.8
Mechanical Characteristics	Rigid

Table III. Dichroic Beam Combiner Characteristics

At present, the dielectric substrate with an IR reflective coating is the best approach of several that have been evaluated. Figure 2 is a drawing that shows how this type of beam combiner is constructed.

Figure 2. Dichroic beam combiner.

The beam combiner consists of an approximately one half inch thick quartz dielectric substrate coated with a very thin multi-layer IR reflective coating. The thickness of the substrate is determined by the range of the IR wavelength and the angle of incidence of the MMW signal. The reflective coating is thin enough to allow the MMW signal to pass unperturbed while providing a high reflection coefficient to the IR in both the mid-wave and long-wave regions of interest. Figure 3 provides a plot of the reflection coefficient for the typical bands of interest.

Figure 4 shows a plot of the transmission losses at various angles for the W-band MMW frequencies. These data provide confidence that the beam combiner simultaneously provides good IR reflection and minimal MMW insertion loss. Practical use of this technology does pose some problems.

Several problems occur because the beam combiner is slanted at an angle relative to the MMW signal and the beam combiner has a finite size. The first problem is easily understood and correctable. In this case, the angular slant leads to unequal reflection coefficients for the vertical and horizontal polarization components of the MMW signal. The polarization error can be corrected during calibration procedures. This correction is accomplished by reducing the amplitude of one polarization component to the equivalent to the other component. This results in the desired circular polarization being transmitted to the seeker instead of an incorrect elliptical polarization. In contrast to the polarization imbalance problem, the finite size of the dichroic element causes less well-behaved phenomena to occur. The problem can be characterized as a diffraction induced error in the apparent angle of arrival of the simulated radar return. This error can not be calibrated out, but has a pseudo random nature as it is directly related to the simulation of glint. An analysis has been performed that indicates the impact to the overall performance of the simulator is relatively minor.

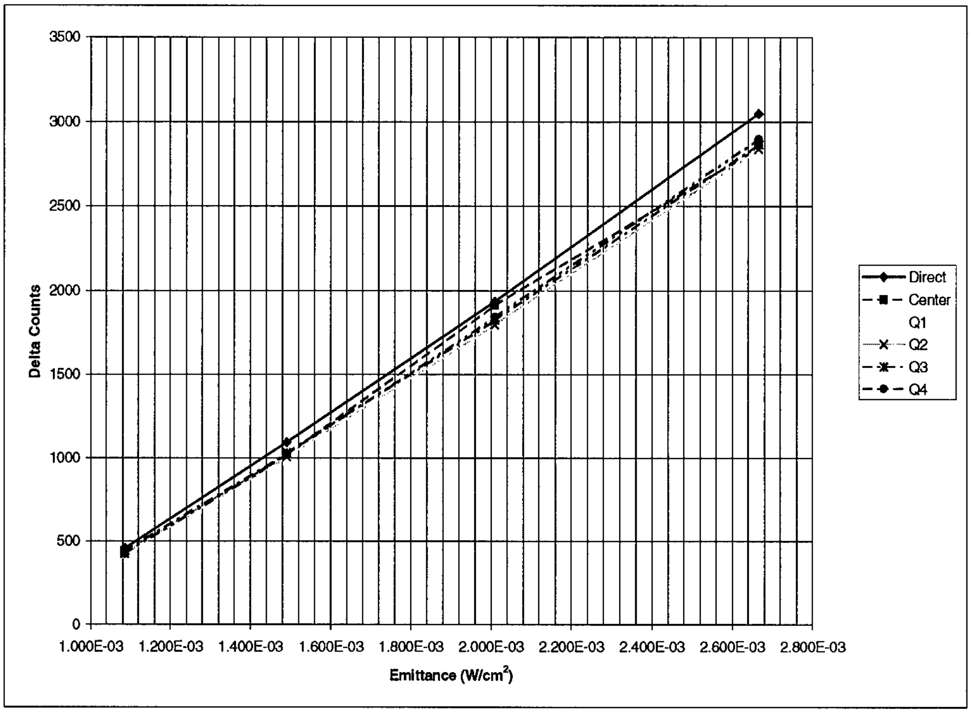

Figure 3. Reflection coefficient of dichroic beam combiner

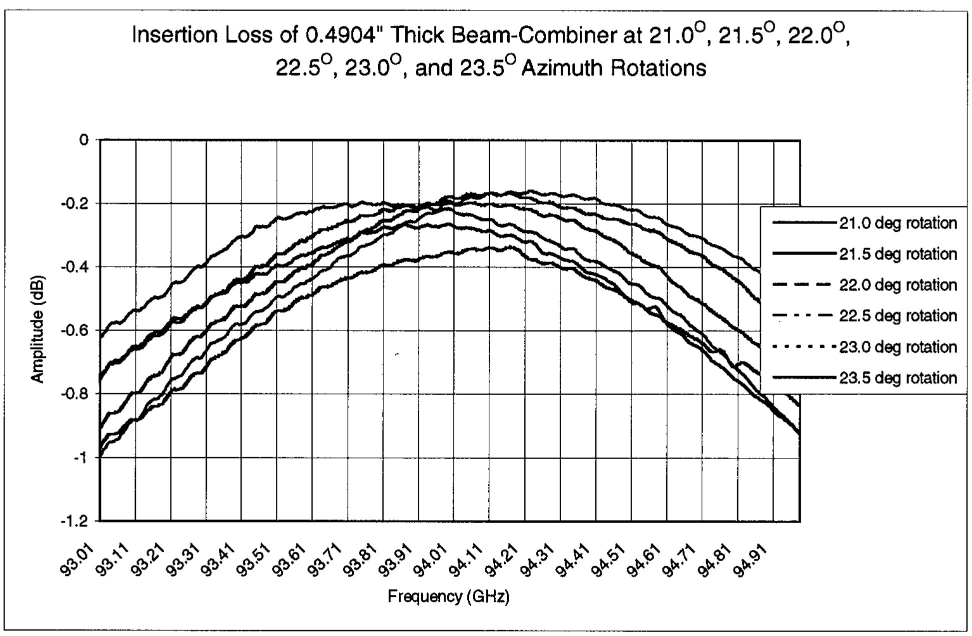

Figure 4. Insertion loss of dichroic beam combineras a function of incidence angle.

DICHROIC SUPPORT STRUCTURE

In addition to the dichroic beam combiner element, a support structure is required. A drawing of the support structure is shown in Figure 5.

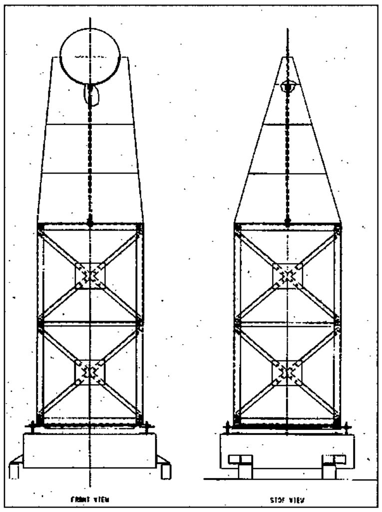

Figure 5. Dichroic support tower.

This figure illustrates the three components of the support structure. These are the isolation pad, the lower support structure, and the upper support/holding structure. The isolation pad is designed to isolate the tower from any vibration or motion. This includes isolation from vibrational or translational motion of the chamber floor caused by the flight table, room air conditioners or other machinery. The isolation pad is a 4ft by 4ft by 1ft volume of steel reinforced concrete encased inside a quarter inch steel frame on the bottom and four sides. Following fabrication of the pad, tests were performed to determine the magnitude of expected displacements at the top of the tower where the dichroic will be positioned. These tests indicated the displacement was minimal and should not be a problem. From accelerometer measurements on the pad itself, it was determined that a spring suspension system was required damp out low frequency vibrations from the flight table. Problems with high frequency vibrations are not anticipated due to the large mass of the isolation pad and the high frequency damping inherent in the spring suspension system. If high frequency vibrations do become a problem, there is sufficient flexibility in the design to add an air damped structure similar to an optical bench between the pad and the lower tower. Although the ideal support tower would be completely transparent to the MMW signals, the magnitude of the problem for the lower portion of the tower is much less than that for the upper portion of the tower as that is where the MMW beam is concentrated. Accordingly, the lower portion of the tower can be constructed out of more types of materials than the top portion of the tower. Numerous tests were performed to determine which materials offered the best performance in terms of MMW transmission and structural rigidity. The results of these tests indicate that an all fiberglass structure for the lower portion of the tower was the best choice. After construction, MMW absorbent material will be placed around the pad and lower portion of the tower. The upper portion of the tower must be as transparent as possible to the MMW signal. For this portion of the tower, polystyrene, which has a dielectric constant nearly equal to free space, was selected. At this time, the main short coming of the support structure is the lack of an optical quality adjustment mechanism to precisely align the beam combiner. The current design includes an adjustment plate between the isolation pad and the lower portion of the tower. This plate allows angular adjustments in the planes of interest through rotation and elevation motion. Finally, cleaning of the dichroic is important. This will be accomplished by extending a retractable platform outward from the flight table

support to the upper portion of the tower.

NEW IR PROJECTOR DEVELOPMENT

A new projector, the Wideband Infrared Scene Projector (WISP) is being integrated into the facility . WISP was developed as part of the Cooperative Test and Evaluation Improvement Program (CTEIP). Figure shows the projector. The rectangular projector is a integrated circuit substrate covered with a 512X512 array of extremely small resistor elements. A current multiplexing circuit is used to selectively heat the resistor element to form the desired image. The elements are well isolated so there is little parasitic heating between elements. Heating and cooling is quite fast due to the small size of the elements. Cooling is enhanced by a closed cycle chilled water cooler that extracts heat from the back of the projector array. Initial function tests of the WISP projector indicates it has excellent dynamic range and uniformity. The update rate may be slower than required for some applications. The WISP projector will be completely evaluated during the next several months. The results will be reported in a subsequent paper. Figure 6 is a photograph of the WISP projector.

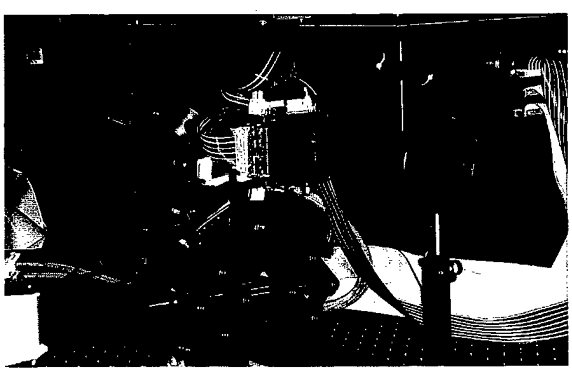

Figure 6. WISP projector.

SUMMARY

This paper has provided a brief overview of the development of a facility at AMCOM to support the HWIL simulations of dual-mode, common-aperture MMW and IR seekers. Three approaches for the dichroic beam combiner have been discussed in terms of performance with advantages and disadvantages being identified to the extent possible. The primary components for the dichroic support structure were also addressed.

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